

## **Estimation of Temporally Evolving Typhoon Winds and Waves from Synthetic Aperture Radar**

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### **LONG-TERM GOALS**

The long term goal is to develop a methodology for using synthetic aperture radar (SAR) data to improve characterization of the winds and waves generated by typhoons in the western Pacific Ocean.

### **OBJECTIVE**

The objective is to develop a variational inversion algorithm based on the SWAN model to estimate the near-surface typhoon wind field from SAR data.

### **APPROACH**

Third-generation wave spectrum models such as SWAN can be used to predict wind-generated waves. Combining SWAN and a model relating the SAR-image spectrum to the computed wave spectrum, one can predict the SAR-image spectrum which results from a known wind field. Using variational techniques, this relationship can be inverted to estimate the wind field from SAR data. This approach uses adjoint versions of the SWAN and SAR models to calculate the gradient of the error of the predicted SAR data with respect to the input wind field. This gradient is used to iteratively adjust the wind field to produce a wave field from SWAN that yields a best-fit to the SAR data.

### **WORK COMPLETED**

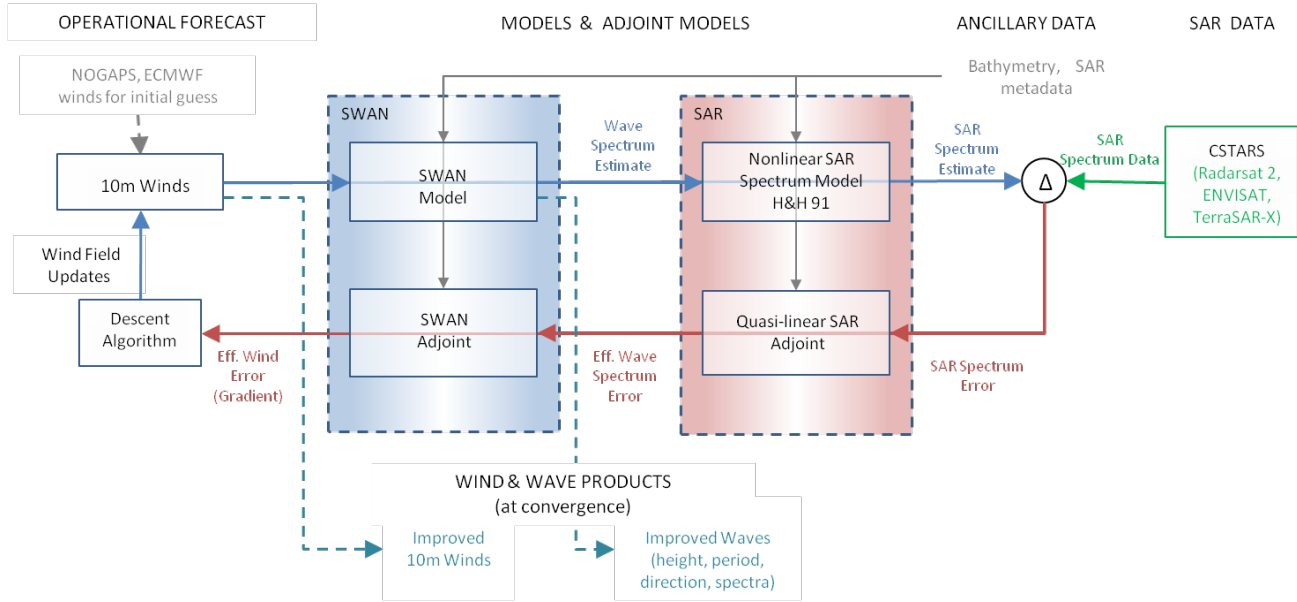
An algorithm for estimation of temporally evolving winds has been developed. The algorithm is variational in nature and is based on the SWAN 40.85 ocean-wave-spectrum model (Ris *et al.* 1999, Booij *et al.* 1999) coupled to the nonlinear SAR-spectrum model of Hasselmann and Hasselmann (1991). An adjoint version of the SWAN model was developed. An expression for the gradient of the cost function (the error in the estimates of the data) with respect to the input wind field in terms of the forward and adjoint solution was derived, and a descent algorithm was implemented to accomplish wind estimation for non-stationary conditions. This required: (1) extension of the SWAN code to efficiently store the entire five-dimensional forward solution; (2) development of a non-stationary adjoint SWAN solver; and (3) development of ancillary codes to calculate the gradient from the forward and adjoint SWAN solutions, adjust the wind field, and control the iteration process. In

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addition, the wind-wave generation modeling in SWAN (Wu 1982) was updated to include high-wind-speed effects on the drag coefficient correlation consistent with the results of Donelan *et al.* (2004).

## RESULTS

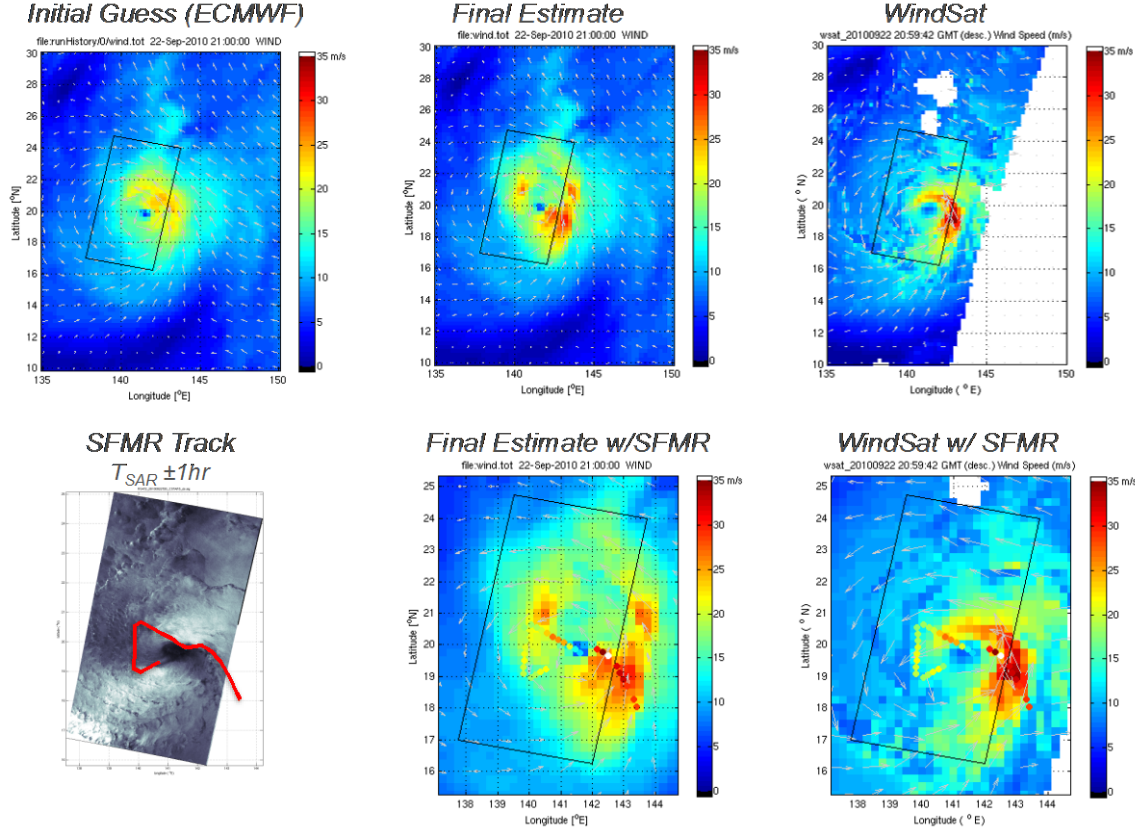
The algorithm structure is shown Figure 1. The algorithm makes use of operation forecast data (as a first guess for winds), models and adjoint models (the SWAN wave spectrum model and the Hasselmann & Hasselmann 1991 SAR spectrum model and corresponding adjoints), ancillary data such as bathymetry, and SAR data (presently obtained from CSTARS). The algorithm outputs are wind and wave products: improved wave spectra and improved estimates of the wind field. Estimates begin with a first guess wind field for the region obtained from operational wind forecasts. An estimate of the wave spectrum and the SAR image spectrum are calculated. The SAR spectrum is compared to that for the data and the difference is fed back through adjoint SAR and SWAN models. The gradient of the error in the estimated SAR spectrum with respect to the wind field is calculated from the adjoint wave spectrum. This gradient is used to adjust the wind field using a descent algorithm and the steps are repeated until the wind field converges and the SAR spectrum is a best fit.



**Figure 1. Algorithm flow chart. The algorithm makes use of operation forecast data (as a first guess for winds), models and adjoint models (the SWAN wave spectrum model and the Hasselmann & Hasselmann 1991 SAR spectrum model and corresponding adjoint models), ancillary data (such as bathymetry), and SAR data, (presently obtained from CSTARS). The algorithm outputs are wind and wave products, improved wave spectra and improved estimates of the wind field.**

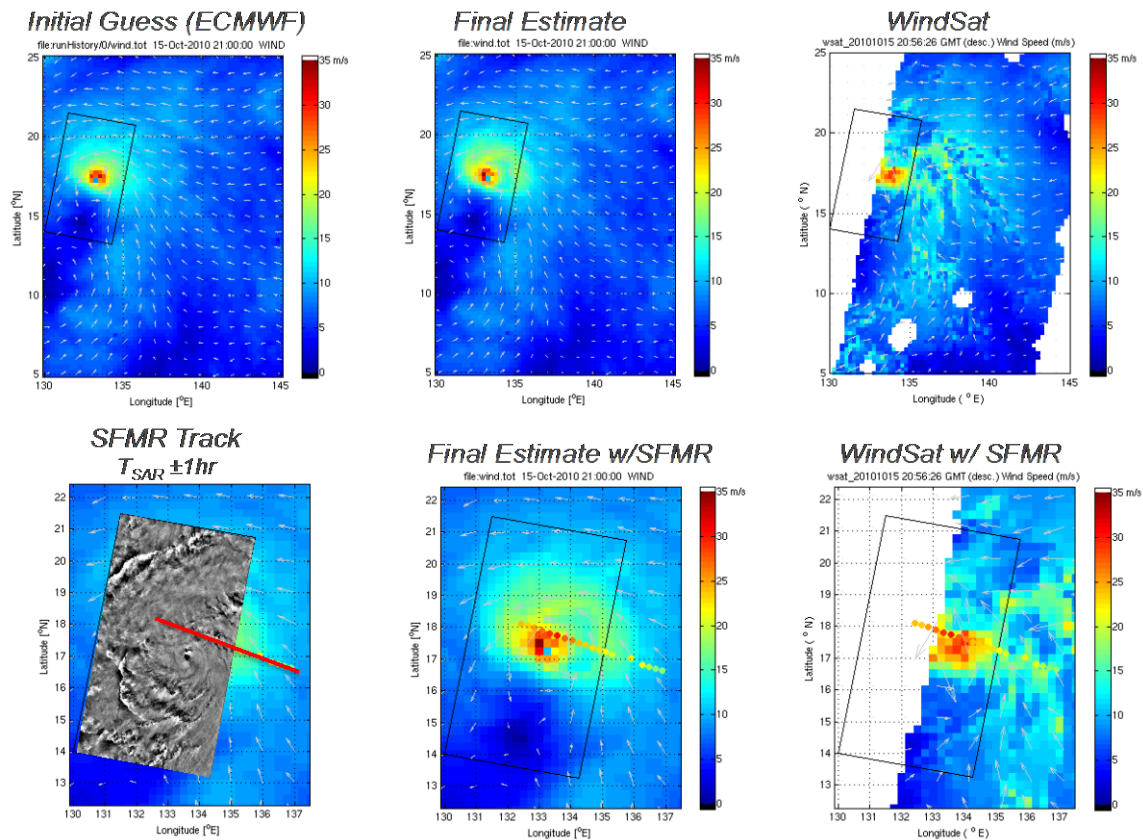
Figure 2 shows results where the algorithm is applied to Radarsat2 data for typhoon Malakas on 22 September 2010. Here the initial guess was from 0.25 degree operational forecast winds from ECMWF. The initial-guess shows maximum winds of 24 m/s while the final algorithm estimate shows maximum winds of 30 m/s, more in agreement with the contemporaneous WindSat data shown in the figure. Figure 2 also shows comparison of the estimated winds to NOAA Stepped Frequency Microwave Radiometer (SFMR) data collected during a flight spanning the time from 1 hour before

the SAR image was acquired to one hour after. These data show good agreement with the velocity magnitude in the southeast quadrant of the storm; the agreement is less good on the west side of the storm. As one would hope there appears to be good agreement between the SFMR and WindSat data. For this case, the maximum significant wave height computed by SWAN increased from 7.8 m for the ECMWF winds to 9.7 m for the more accurate SWAN-SAR winds.



**Figure 2 Results from SWAN-SAR estimation algorithm for typhoon Malakas on 22 September 2010. The upper row shows comparison of initial-guess winds, final estimated winds based on Radarsat2 SAR data, and contemporaneous WindSat radiometer data; for the SWAN-SAR estimate, maximum winds have increased from 24 m/s to 30 m/s, similar to the WindSat maximum wind speed. The lower row shows SFMR track plotted on the SAR image and comparison of SFMR data to the SWAN-SAR estimate and WindSat data, showing good agreement for both.**

Figure 3 shows similar algorithm results for Radarsat2 data collected during typhoon Megi on 15 October 2010. The initial guess was again from 0.25 degree operational forecast winds from ECMWF. The initial guess has maximum winds of 32 m/s while the final algorithm estimate shows maximum winds of 35 m/s. The contemporaneous WindSat data shown in the figure has maximum winds of 33 m/s, so where the initial-guess winds are slightly low, the final estimated winds are slightly high, but the algorithm did not change them significantly, which is good. Figure 3 also shows comparison of the estimated winds to SFMR data collected during a flight spanning the time from 1 hour before the SAR image was acquired to one hour after. There is limited overlap with the storm during this time period, but the data show good agreement with the estimated velocity. Again, there appears to be good agreement between the SFMR and WindSat data. For this case, the maximum significant wave height computed by SWAN was unchanged for the SWAN-SAR winds.



**Figure 3 Results from SWAN-SAR estimation algorithm for typhoon Megi on 15 October 2010.** The upper row shows comparison of initial-guess winds, final estimated winds based on Radarsat2 SAR data, and contemporaneous WindSat radiometer data; for the SWAN-SAR estimate, here the size and shape of the storm has changed slightly, but the maximum winds for the initial guess nearly matched the WindSat data are left relatively unchanged by the algorithm. Lower row shows SFMR track plotted on SAR image and comparison of SFMR data to SWAN-SAR estimate and WindSat data, showing good agreement for both.

In the coming year the SWAN-SAR algorithm will be applied to a number of other storms for which we have SAR data, and the performance of the algorithm will be characterized more completely.

## IMPACT/APPLICATIONS

The algorithm developed here may enable improved operational prediction of tropical cyclone evolution.

## RELATED PROJECTS

This program is part of the ITOP Departmental Research Initiative

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